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SUMMARY

The effects of 22 and 40 MeV proton bombardments on n- and p-type single-crystal germanium were investigated. Electrical conductivity and the Hall coefficient were measured as a function of proton flux to provide removal rates for majority carriers. A defect energy level was located in n-type germanium 0.20 eV ±0.01 eV below the bottom of the conduction band from a study of the Hall coefficient as a function of temperature and, also, from a study of the removal rate of electrons as a function of the Fermi level. The rate of introduction of acceptor levels in n-type germanium was found to be 73.5 per cm-proton for irradiation with 22 MeV protons and 41.4 per cm-proton for irradiation with 40 MeV protons.

The measured removal rates of holes in p-type germanium were much lower than the removal rates of electrons in n-type germanium at a similar resistivity and for the same bombarding particles. A limiting value of the Fermi level was located between 0.20 eV and 0.25 eV above the top of the valence band.

INTRODUCTION

The effects of radiation on semiconductors have been extensively studied. However, studies of proton damage have been limited. The investigation of proton damage to germanium transistors has indicated a need for a better understanding of defects produced in the constituent materials of these devices by high-energy protons (ref. 1). For this reason, bombardment of germanium by 22 and 40 MeV protons and the study of the resulting lattice defects were undertaken.

Measurements were made of electrical conductivity and the Hall coefficient since both are very sensitive to defects produced in the lattice of the semiconductor by radiation. Only permanent defects were considered in these studies, that is, defects arising from the production of interstitials and vacancies by the incident protons and their resulting recoil atoms. These defects give rise to trapping sites and recombination centers in the germanium. However, in this report only the trapping of majority carriers from either the conduction band or the valence band will be considered.

For the bombardment phase of the experiments, the 22 MeV cyclotron at the Oak Ridge National Laboratory and the 40 MeV linear accelerator at the University of Minnesota were utilized.

SYMBOLS

a_h	Bohr radius of hydrogen atom
E	energy of proton
E_A	energy of acceptor
E_C	energy at bottom of conduction band
E_D	energy of donor
E_d	displacement energy
E_F	Fermi level
E_i	energy of bombardment-produced acceptor
E_j	energy of bombardment-produced donor
E_{max}	maximum energy that can be transferred to recoil atom
E_V	energy at top of valence band
$\bar{E}_R$	mean energy of recoil atom
e	electronic charge
f	Fermi function
h	Planck constant
k	Boltzmann constant
m	mass of proton
m_{Ge}	mass of germanium atom
m_H	mass of "heavy" hole
m_L	mass of "light" hole

m_l	longitudinal mass of electron
m_n	effective mass of electron
m_o	mass of free electron
m_p	effective mass of hole
m_t	transverse mass of electron
N	number of atoms per cubic centimeter
N_A	concentration of acceptors
$N_{A,i}$	concentration of bombardment-produced acceptors
$N_{A,o}$	concentration of acceptors prior to bombardment
$\frac{dN_A}{d\phi}$	rate of introduction of acceptors
N_C	effective concentration of available states in conduction band
N_d	number of displacements produced per centimeter per particle
$N_{D,j}$	concentration of bombardment-produced donors
$N_{D,o}$	concentration of donors prior to bombardment
N_V	effective concentration of available states in valence band
n	concentration of conduction electrons
n_o	initial concentration of conduction electrons
$\left(\frac{dn}{d\phi}\right)_o$	initial removal rate of electrons
p	concentration of holes
p_o	initial concentration of holes
$\left(\frac{dp}{d\phi}\right)_o$	initial removal rate of holes
R_H	Hall coefficient

R_h	Rydberg energy for hydrogen atom
r	ratio of Hall mobility to drift mobility
T	temperature in $^{\circ}K$
Z	atomic number of target atoms
γ	spin degeneracy
γ_i	spin degeneracy of acceptor level
γ_j	spin degeneracy of donor level
μ_n	electron mobility
μ_p	hole mobility
$\bar{\nu}_d$	mean number of displacements per primary recoil atom
σ	electrical conductivity
σ_d	total displacement cross section
σ_o	initial electrical conductivity
ϕ	integrated flux

DESCRIPTION OF EXPERIMENTAL TECHNIQUE

Commercially zone-leveled germanium in the form of ingots was used in this investigation. The ingots were sliced into 25-mil-thick wafers with a diamond cutoff wheel. Bridge samples were cut from these wafers by an ultrasonic cutter. The samples were lapped to a thickness of approximately 15 mils; the thickness of each sample was measured by a micrometer. Next, the germanium samples were etched in a standard chemical etch (five parts HF, five parts acetic acid, and eight parts HNO_3). Leads were attached to the tabs of the samples by indium-alloy solder, and the samples were mounted on ceramic substrates for ease of handling (fig. 1).

For the bombardment phase of the experiment, the 22 MeV cyclotron at the Oak Ridge National Laboratory (ref. 2) and the 40 MeV linear accelerator at the University of Minnesota (ref. 3) were utilized. During bombardment the germanium samples were mounted in a Hall magnet, and the proton beam was allowed to impinge on the sample by passing it through a hole in the pole piece of the magnet. (See fig. 2.) A thin scattering foil was used to spread the proton beam over a large area. The beam was then collimated to a 3/8-inch diameter to insure uniformity of flux. The 40 MeV proton flux was measured directly by a Faraday cup mounted behind the sample, as proton scatter from the sample was negligible. However, for the 22 MeV bombardments, the collimator was calibrated against the Faraday cup, and the beam current was monitored by the collimator. (See fig. 2.) Pertinent electrical parameters of the samples were measured during periodic interruption of the radiation cycle. The magnetic field for the Hall coefficient determinations was maintained at 5000 gauss during this phase of the experiment. The accuracy of the voltage and current measurements on the test samples was 1 percent or better.

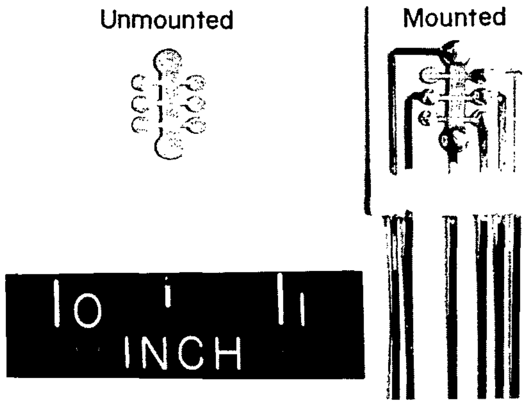

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Figure 1.- Germanium bridge sample used for electrical conductivity and Hall coefficient measurements.

The Hall coefficient as a function of temperature was determined at Langley Research Center prior and subsequent to bombardment. The temperatures of the samples were monitored by measuring the output voltage of a copper-constantan thermocouple attached directly to the sample. The lower temperatures were controlled by means of a liquid nitrogen bath and a heater coil, which was wound around the chamber enclosing the sample. For temperatures closer to room temperature, dry ice was substituted for the liquid nitrogen bath. By using this type of temperature control system, the temperature could be maintained to $\pm 1^{\circ}$ C. The magnetic fields for the Hall coefficient measurements were maintained at 3000 gauss.

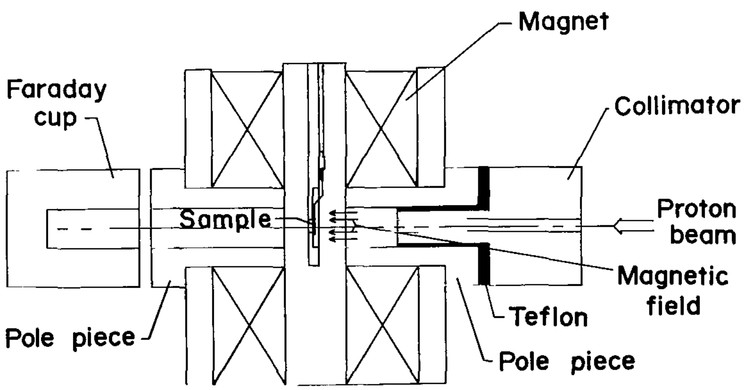


Figure 2.- Experimental setup for measuring the Hall coefficient and electrical conductivity during proton bombardment.

DISCUSSION OF THEORY

Simple Displacement Theory (Refs. 4 and 5)

A theory for displacements produced by radiation is formulated in references 4 and 5.

High-energy proton bombardment causes permanent damage in germanium by the displacement of the germanium atoms from their normal lattice sites to form interstitials and vacancies. Displacements are produced by a primary and a secondary process. The primary process is the direct coulomb interaction of the proton and the germanium nucleus. The secondary process is an interaction of the resulting recoil atom with nearby atoms. For energetic protons, the secondary process accounts for the majority of the displaced atoms.

The total number of displacements produced per centimeter per particle is given by

$$N_d = N\sigma_d\bar{\nu}_d \tag{1}$$

where σ_d is the total displacement cross section, N is the number of atoms per cubic centimeter, and $\bar{\nu}_d$ is the mean number of displacements per primary recoil atom.

For the proton energies of concern in this report, the displacement cross section may be calculated from the unscreened coulomb potential. For nonrelativistic particles, the displacement cross section is given by

$$\sigma_d = 4\pi a_h^2 \frac{m}{m_{Ge}} \frac{Z^2R_h^2}{EE_d} \tag{2}$$

where

a_h	Bohr radius of hydrogen atom
m	mass of proton
m_{Ge}	mass of germanium atom
R_h	Rydberg energy for hydrogen atom
E	energy of proton
E_d	displacement energy, 30 eV
Z	atomic number of target atoms

The mean number of atoms displaced per primary recoil atom was estimated from the Kinchin and Pease model (ref. 5) to be

$$\bar{\nu}_d \approx \frac{\bar{E}_R}{2E_d} \tag{3}$$

The mean energy of the recoil atom, $\bar{E}_R$, is given by

$$\bar{E}_R = E_d \ln\left(\frac{E_{max}}{E_d}\right) \tag{4}$$

where E_{max}, the maximum energy that can be transferred to the recoil atom, is

$$E_{max} = \frac{4mm_{Ge}}{\left(m + m_{Ge}\right)^2} E \tag{5}$$

The contributions to the total number of displacements produced due to nuclear inelastic scattering and spallation have been neglected since they are quite small at 22 and 40 MeV.

Semiconductor Theory

In order to investigate proton damage to germanium, measurements of the electrical conductivity and the Hall coefficient were made. In a semiconductor the electrical conductivity is defined as

$$\sigma = e\left(n\mu_n + p\mu_p\right) \tag{6}$$

where n is the concentration of conduction electrons, p is the concentration of holes, and μ_n and μ_p are the respective mobilities of the electrons and holes. In this report, only germanium samples where the concentration of one type of carrier is negligible in comparison with that of the other are considered. Therefore, the expression for the electrical conductivity reduces to either

$$\left.\begin{aligned} \sigma &= ne\mu_n \\ \text{or} \qquad \sigma &= pe\mu_p \end{aligned}\right\} \tag{7}$$

For a semiconductor, the Hall coefficient is in general given by the following expression:

$$R_H = \frac{r\left(p\mu_p^2 - n\mu_n^2\right)}{e\left(p\mu_p + n\mu_n\right)^2} \tag{8}$$

where r is the ratio of the Hall mobility to the drift mobility and is taken to be $3\pi/8$ in this investigation. In a typical semiconductor, R_H reduces to either $-r/ne$ or r/pe.

From Fermi-Dirac statistics,

$$p = N_V e^{\left(E_V - E_F\right)/kT} \tag{9}$$

for holes, and

$$n = N_C e^{-\left(E_C - E_F\right)/kT} \tag{10}$$

for electrons where N_C and N_V are the effective concentrations of states available in the conduction band and valence band, respectively, and

$$\left.\begin{aligned} N_C &= \frac{2(2\pi m_n kT)^{3/2}}{h^3} \\ N_V &= \frac{2(2\pi m_p kT)^{3/2}}{h^3} \end{aligned}\right\} \tag{11}$$

The effective mass of the electrons, m_n, is given as

$$m_n = 4^{2/3}\left(m_l m_t^2\right)^{1/3} = 0.56m_o$$

where $m_l = 1.64m_o$ and $m_t = 0.082m_o$ (see ref. 6), and the effective mass of the holes, m_p, is given as

$$m_p = \left(m_L^{3/2} + m_H^{3/2}\right)^{2/3} = 0.37m_o$$

where $m_L = 0.043m_o$ and $m_H = 0.36m_o$ (see ref. 7).

Defect Energy Level Theory

When a semiconductor is bombarded, defects (interstitials and vacancies) are introduced which give rise to electronic levels in the forbidden gap of the material. According to the model of James and Lark-Horovitz (ref. 8), two donor levels and two acceptor levels are introduced. The two donor levels, one shallow level above the middle of the forbidden gap and one deeper-lying level, are attributed to the isolated interstitial. The two acceptor levels are assigned to the isolated vacancy; both are located below the middle of the gap. A model proposed later by Blount (refs. 9 and 10) allows the interstitials and vacancies to act either as acceptors or donors. Only isolated vacancies and interstitials are considered in these models. Normally, radiation-produced defects are considerably more complex.

The probability that a donor will be filled with an electron is $f = \dfrac{1}{1 + \gamma e^{(E_D - E_F)/kT}}$ whereas the probability that an acceptor will be occupied by a hole is $f = \dfrac{1}{1 + \gamma e^{(E_F - E_A)/kT}}$ where E_D and E_A are the respective energies of the donor and the acceptor and γ is the spin degeneracy. The condition of electrical neutrality after bombardment is fulfilled by the following general expression (ref. 11):

$$n - p = N_{D,o} - N_{A,o} + \sum_j \left[\frac{N_{D,j}}{1 + \gamma_j^{-1} e^{(E_F - E_j)/kT}} \right] - \sum_i \left[\frac{N_{A,i}}{1 + \gamma_i^{-1} e^{(E_i - E_F)/kT}} \right] \tag{12}$$

where $N_{D,o}$ and $N_{A,o}$ are the concentrations of ionized donors and acceptors existing prior to bombardment and where $N_{D,j}$ and $N_{A,i}$ are the concentrations of bombardment-produced donors and acceptors.

In this investigation two experimental techniques have been employed to determine the location of defect energy levels. The first approach was to investigate the temperature dependence of the majority-carrier concentration. As the temperature is varied, the Fermi level shifts and, thus, the probability of occupation of the defect level is changed. When the Fermi level passes over the defect level, the concentration of the carriers available for conduction changes abruptly, usually within 1 or 2kT of the defect level. The concentration of conduction electrons is given as

$$n = N_C e^{-(E_C - E_F)/kT} = N_C e^{-(E_C - E_A)/kT} e^{(E_F - E_A)/kT} = \frac{2(2\pi m_n kT)^{3/2}}{h^3} e^{-(E_C - E_A)/kT} e^{(E_F - E_A)/kT}$$

Thus,

$$nT^{-3/2} = \frac{2(2\pi m_n k)^{3/2}}{h^3} e^{-(E_C - E_A)/kT} e^{(E_F - E_A)/kT}$$

and

$$\ln\left(nT^{-3/2}\right) = \ln \frac{2(2\pi m_n k)^{3/2}}{h^3} - \frac{E_C - E_A}{kT} + \frac{E_F - E_A}{kT}$$

Assume that E_F is very close to E_A so that

$$\left|\frac{E_F - E_A}{kT}\right| \ll \left|\frac{E_C - E_A}{kT}\right|$$

Therefore,

$$\ln\left(nT^{-3/2}\right) \approx \ln\left[\frac{2(2\pi m_n k)^{3/2}}{h^3}\right] - \frac{E_C - E_A}{kT}$$

$$\frac{d\left[\ln\left(nT^{-3/2}\right)\right]}{d(1/T)} \approx -\frac{E_C - E_A}{k} \tag{13}$$

Thus, a plot of $\ln\left(nT^{-3/2}\right)$ as a function of $1/T$ would reveal the location of the defect level.

The second experimental technique utilized to determine defect energy levels was the study of the removal rate of majority carriers as a function of the Fermi level. With the assumption that two acceptor and two donor levels are introduced asymmetrically in the forbidden gap (one shallow acceptor level below the conduction band and the other levels below the middle of the forbidden gap), the equation for the concentration of conduction electrons for n-type germanium is

$$n = N_{D,o} - N_{A,o} - N_A\left[\frac{1}{1 + e^{(E_A - E_F)/kT}} + 1\right] \tag{14}$$

for the following conditions:

(a) $p \ll n$ and can be neglected.

(b) $e^{(E_F-E_j)/kT}$ is large; that is, both donor levels are far below E_F, and $\sum_{j=1}^{2}\left[\frac{N_{D,j}}{1+\gamma_j^{-1}e^{(E_F-E_j)/kT}}\right]$ can be neglected.

(c) The shallow acceptor is partially filled with electrons whereas the deeper acceptor is completely filled.

(d) The number of shallow acceptors is equal to the number of deep-lying acceptors.

(e) The value of γ_i is taken to be unity.

Therefore, the expression for the initial removal rate of conduction electrons becomes

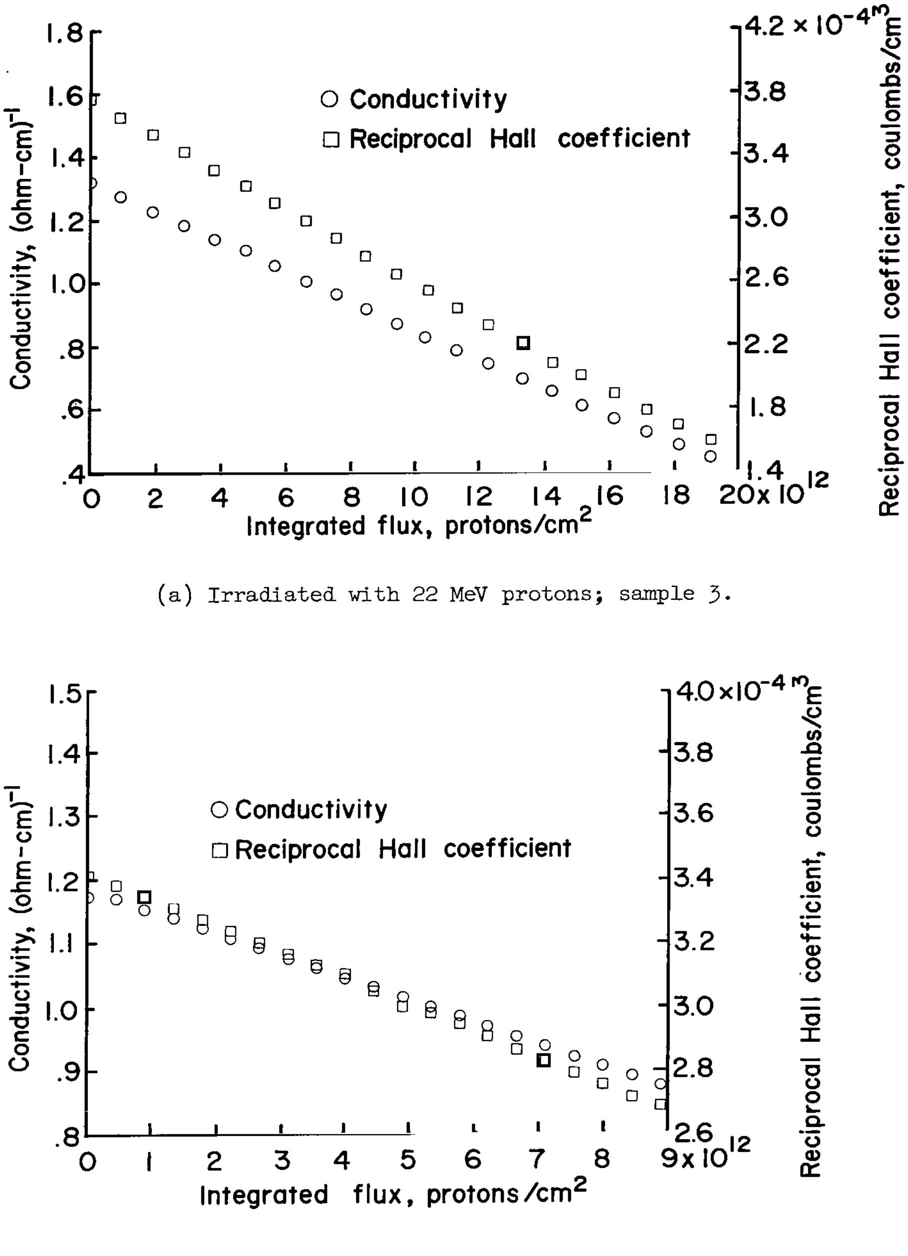
$$\left(\frac{dn}{d\phi}\right)_o = -\frac{dN_A}{d\phi}\left[\frac{1}{1+e^{(E_A-E_F)/kT}}+1\right] \tag{15}$$

This expression can be used to obtain a best theoretical fit to an experimental plot of initial removal rate of conduction electrons as a function of the initial Fermi level. This theoretical fit yields the location of the shallow acceptor level and the introduction rate of these acceptors.

RESULTS AND DISCUSSION

n-Type Germanium

Samples of arsenic-doped, n-type germanium with resistivities in the range from 0.069 to 15.9 ohm-cm were irradiated with 22 and 40 MeV protons at room temperature. The Hall coefficient and electrical conductivity were determined at regular intervals during the bombardment. The proton beam was not appreciably degraded as it passed through the relatively thin samples. Examples of results obtained as a function of integrated proton flux are shown in figure 3. Figure 3(a) indicates radiation-produced changes in the conductivity and Hall coefficient for a germanium sample which had an initial resistivity of 0.76 ohm-cm. This sample was bombarded with 22 MeV protons to an integrated flux of 1.91×10^{13} protons/cm^2. The calculated initial removal rate of electrons from the conduction band was -92.9 electrons/cm-proton. Figure 3(b) shows changes in the identical parameters for a germanium sample, with an initial resistivity of 0.85 ohm-cm, irradiated with 40 MeV protons to an integrated flux of 8.88×10^{12} protons/cm^2. The calculated initial removal rate of conduction electrons was -57 electrons/cm-proton.



(a) Irradiated with 22 MeV protons; sample 3.

(b) Irradiated with 40 MeV protons; sample 8.

Figure 3.- Conductivity and reciprocal Hall coefficient as a function of integrated proton flux. Arsenic-doped n-type germanium.

The results of bombardment of n-type germanium for both the 22 and 40 MeV irradiations are summarized in table 1. As can readily be seen, the initial removal rate of conduction electrons is a function of the initial Fermi level. The removal rate ranges from -137.3 electrons/cm-proton for an initial Fermi level of E_C - 0.147 eV to -56.8 electrons/cm-proton for an initial Fermi level of 0.287 eV below the bottom of the conduction band for the 22 MeV bombardment. In figure 4 the slope of the straight part of the curve obtained subsequent to bombardment points out the existence of a level in n-type germanium 0.20 eV below the bottom of the conduction band not seen prior to irradiation. This level has been found by other investigators using other types of bombarding radiation. Results presented in references 5 and 12 indicate that this is an acceptor level.

TABLE 1.- INITIAL REMOVAL RATES OF ELECTRONS FOR n-TYPE GERMANIUM WITH VARYING INITIAL FERMI LEVELS

Sample	σ_o, (ohm-cm)$^{-1}$	n_o, cm^{-3}	Initial Fermi level, eV	$\left(\frac{dn}{d\phi}\right)_o$, $\frac{\text{electrons}}{\text{cm-proton}}$
Bombardment with 22 MeV protons at 299° K				
1	14.5	3.62×10^{16}	E_C - 0.147	-137.3
2	12.9	3.04×10^{16}	E_C - 0.151	-150.3
3	1.32	2.78×10^{15}	E_C - 0.214	-92.9
4	1.14	2.26×10^{15}	E_C - 0.219	-92.0
5	.089	1.92×10^{14}	E_C - 0.283	-70.2
6	.078	1.84×10^{14}	E_C - 0.287	-56.8
Bombardment with 40 MeV protons at 296° K				
7	12.1	3.39×10^{16}	E_C - 0.144	-88.3
8	1.17	2.51×10^{15}	E_C - 0.213	-57.0
9	1.08	2.33×10^{15}	E_C - 0.215	-70.8
10	.071	1.50×10^{14}	E_C - 0.278	-40.4
11	.063	1.36×10^{14}	E_C - 0.283	-38.0

By using the initial removal rates from table 1 and by assuming different values of E_A from E_C - 0.18 eV to E_C - 0.24 eV, values of $\frac{dN_A}{d\phi}$ were calculated which corresponded to those of E_A. Then, a theoretical fit to the experimental points was obtained by using equation (15). Figure 5(a) shows a plot of initial removal rate of electrons as a function of initial Fermi level for the 22 MeV proton bombardment. The best theoretical curve was obtained for

$E_A = E_C - 0.19$ eV and $\frac{dN_A}{d\phi} = 73.5$ acceptors/cm-proton. A similar procedure was conducted for the 40 MeV bombardment; the results are shown in figure 5(b). For the 40 MeV bombardment, the best theoretical curve was obtained for

$E_A = E_C - 0.21$ eV and $\frac{dN_A}{d\phi} = 41.4$ acceptors/cm-proton.

The rate of introduction of acceptors can be used to compare the relative damage at the two proton energies. Thus,

$$\frac{\left(\frac{dN_A}{d\phi}\right)_{22}}{\left(\frac{dN_A}{d\phi}\right)_{40}} = 1.78$$

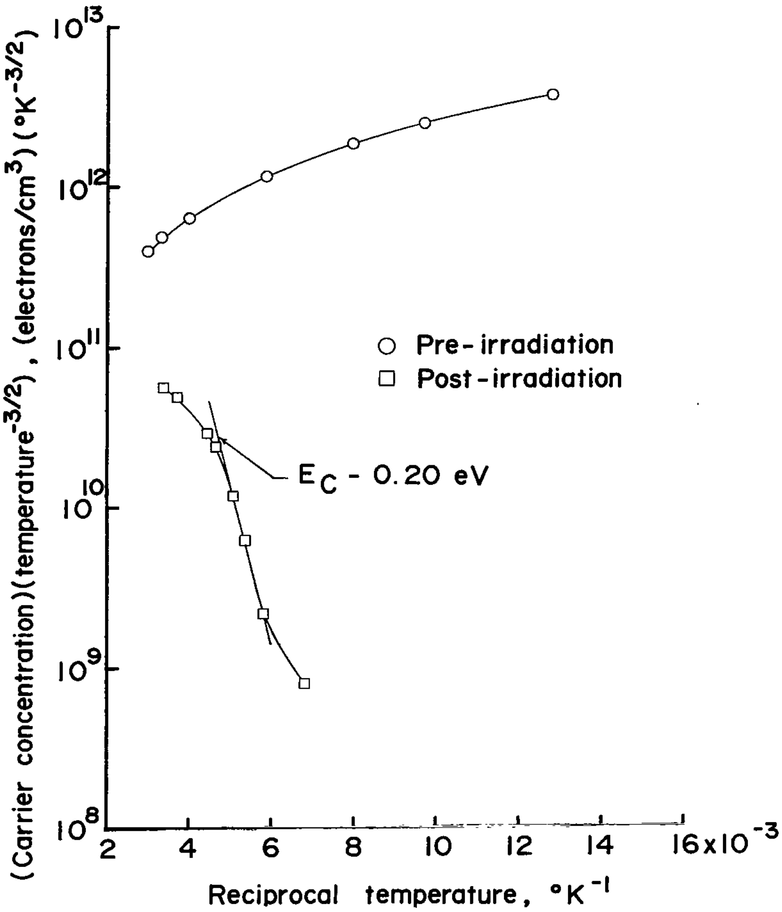


Figure 4.- Location of a defect energy level by means of a plot of $nT^{-3/2}$ as a function of $1/T$. Arsenic-doped n-type germanium irradiated with 22 MeV protons; $\phi = 3.10 \times 10^{13}$ protons/cm^2; sample 22.

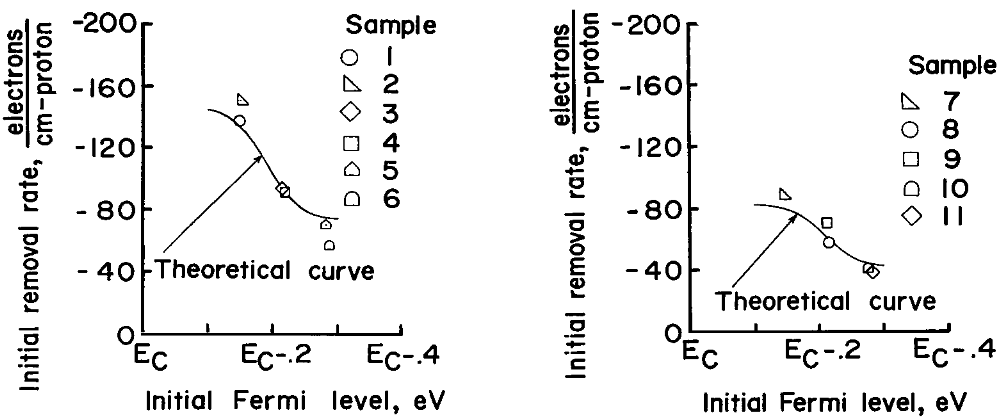
Theoretically, the number of displacements/cm-proton at 22 MeV compared with that at 40 MeV is $\dfrac{(N_d)_{22}}{(N_d)_{40}}$. Making use of equation (1) yields:

$$\frac{\left(N_d\right)_{22}}{\left(N_d\right)_{40}} = \frac{N\left(\sigma_d\bar{\nu}_d\right)_{22}}{N\left(\sigma_d\bar{\nu}_d\right)_{40}} = \frac{\left(\sigma_d\bar{\nu}_d\right)_{22}}{\left(\sigma_d\bar{\nu}_d\right)_{40}}$$

Substitution for σ_d and $\bar{\nu}_d$ results in the following expression:

$$\frac{(N_d)_{22}}{(N_d)_{40}} = \frac{E_{40}(\bar{E}_R)_{22}}{E_{22}(\bar{E}_R)_{40}} = 1.72$$

The fairly close agreement between theory and experiment indicates that coulomb interactions are principally responsible for the production of defects in the energy range of this investigation.



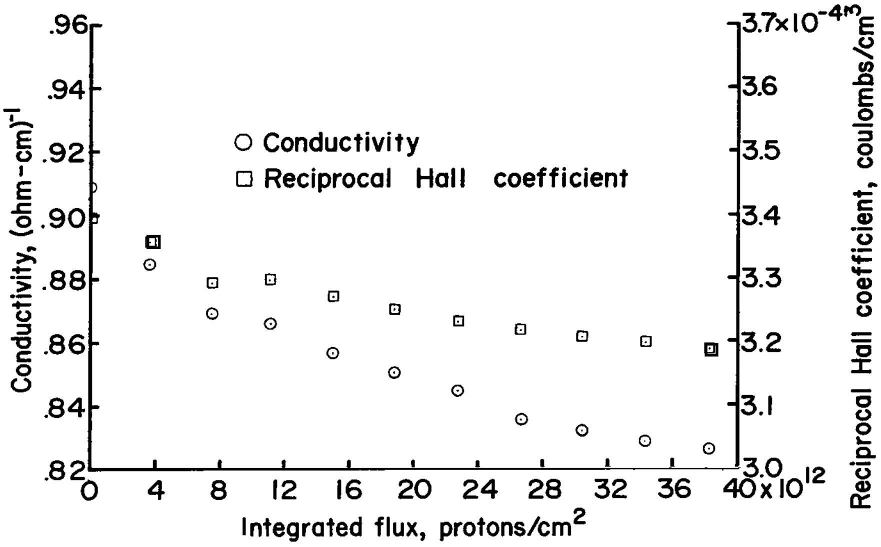
(a) Irradiated with 22 MeV protons.

(b) Irradiated with 40 MeV protons.

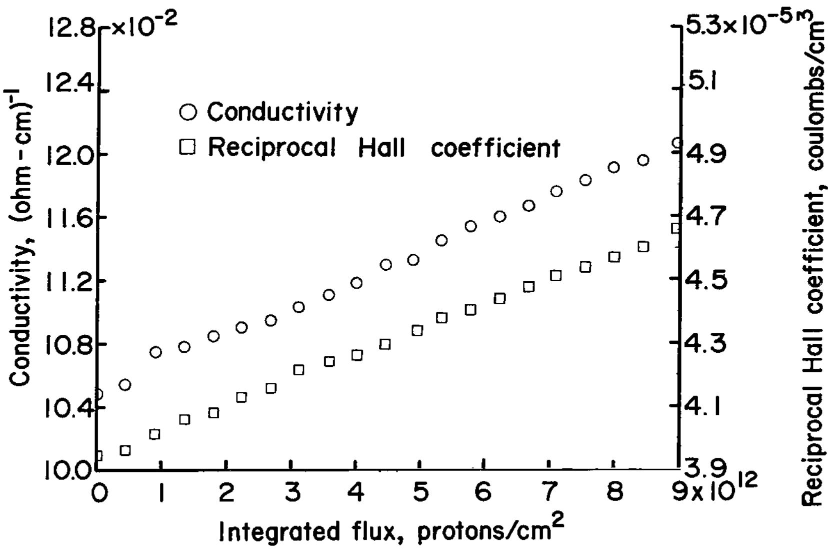
Figure 5.- Application of equation (15) to experimental data to obtain defect energy level and acceptor introduction rate. n-type germanium.

p-Type Germanium

Several samples of indium-doped, p-type germanium with a range of resistivities from 0.089 to 9.80 ohm-cm were also bombarded with 22 and 40 MeV protons at room temperature. Conductivity and reciprocal Hall coefficient changes during bombardment with 22 MeV protons are shown in figure 6(a). This sample had an initial resistivity of 1.10 ohm-cm. Both the conductivity and the reciprocal Hall coefficient decreased under bombardment because of the removal of holes from the valence band. The rate of the removal of holes was -8.0 holes/cm-proton. A similar plot is shown in figure 6(b) for a sample, with an initial resistivity of 9.54 ohm-cm, bombarded with 40 MeV protons. However, both the conductivity and reciprocal Hall coefficient increased during bombardment, an indication that holes were being introduced into the valence band. The introduction rate of holes was 5.4 holes/cm-proton.



(a) Irradiated with 22 MeV protons; sample 15.



(b) Irradiated with 40 MeV protons; sample 20.

Figure 6.- Conductivity and reciprocal Hall coefficient as a function of integrated proton flux. Indium-doped p-type germanium.

The results of the bombardment of p-type germanium are summarized in table 2. As can be seen from the table, for the 22 MeV bombardment, the removal rate changes from a negative value to a positive value between values of the initial Fermi level of $E_V + 0.202$ eV and $E_V + 0.252$ eV. This change points out the existence of a limiting value of the Fermi level between these two values; this limiting value is that value of the Fermi level for which the removal rate of the carriers is zero. It can also be seen from tables 1 and 2 that the removal rates for holes are much lower than those for electrons at a similar resistivity and bombardment energy.

TABLE 2.- INITIAL REMOVAL RATES OF HOLES FOR p-TYPE GERMANIUM WITH VARYING INITIAL FERMI LEVELS

Sample	σ_o, $(\text{ohm-cm})^{-1}$	p_o, cm^{-3}	Initial Fermi level, eV	$\left(\frac{dp}{d\phi}\right)_o$, $\frac{\text{holes}}{\text{cm-proton}}$
Bombardment with 22 MeV protons at 299° K				
12	10.6	4.62×10^{16}	$E_V + 0.125$	-25.3
13	8.76	3.62×10^{16}	$E_V + 0.132$	-19.7
14	.946	2.67×10^{15}	$E_V + 0.201$	-8.4
15	.909	2.50×10^{15}	$E_V + 0.202$	-8.0
16	.126	3.50×10^{14}	$E_V + 0.252$	13.9
17	.110	3.22×10^{14}	$E_V + 0.255$	7.3
Bombardment with 40 MeV protons at 296° K				
18	11.2	5.07×10^{16}	$E_V + 0.120$	-12.6
19	9.71	4.23×10^{16}	$E_V + 0.124$	-21.6
20	.105	2.90×10^{14}	$E_V + 0.253$	5.4
21	.102	2.92×10^{14}	$E_V + 0.253$	7.5

CONCLUDING REMARKS

In the determination of the defect introduction rate, the tacit assumption was made that the rate of introduction of acceptors could be taken as the defect introduction rate. This assumption may not be completely correct, but it has been made in order that the ratio of damage produced with 22 MeV protons to that produced with 40 MeV protons determined experimentally could be compared with that for theory. The damage at 22 MeV relative to that at 40 MeV compares well with theory.

The defect energy level located 0.20 eV ±0.01 eV below the bottom of the conduction band was labeled an acceptor on the basis of the results of previous studies made by other investigators. If the level had been assumed to be a donor, the fit of the theoretical curve to the experimental plot of initial removal rate as a function of initial Fermi level would not be altered for the following assumptions: (1) The concentration of radiation-produced donors equals the concentration of radiation-produced acceptors. (2) The spin degeneracy is unity. Any other values of the spin degeneracy would only shift slightly the value determined for the defect energy level.

In future investigations it would be desirable to determine values of the removal rate for a more extensive range of the Fermi level. As a result, more accurate determinations of defect energy levels could be made, and the limiting value of the Fermi level could be determined.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., November 13, 1964.

REFERENCES

1. Honaker, William C.; and Bryant, Floyd R.: Irradiation Effects of 40 and 440 Mev Protons on Transistors. NASA TN D-1490, 1963.

2. Martin, John A.; Livingston, Robert S.; Murray, Raymond L.; and Rankin, Mozelle: Radioisotope Production Rates in a 22-Mev Cyclotron. Nucleonics, vol. 13, no. 3, Mar. 1955, pp. 28-32.

3. Hamman, Donald J.; and Veazie, Walter H., Jr.: Survey of Particle Accelerators. REIC Rept. No. 31 (Pt. II), Battelle Mem. Inst., Sept. 15, 1963.

4. Seitz, Frederick; and Koehler, J. S.: Displacement of Atoms During Irradiation. Solid State Physics, Vol. 2, Frederick Seitz and David Turnbull, eds., Academic Press, Inc. (New York), 1956, pp. 305-448.

5. Billington, Douglas S.; and Crawford, James H., Jr.: Radiation Damage in Solids. Princeton Univ. Press, 1961.

6. Dexter, R. N.; Zeiger, H. J.; and Lax, Benjamin: Cyclotron Resonance Experiments in Silicon and Germanium. Phys. Rev., Second ser., vol. 104, no. 3, Nov. 1, 1956, pp. 637-644.

7. Lax, Benjamin; and Mavroides, J. G.: Statistics and Galvanomagnetic Effects in Germanium and Silicon With Warped Energy Surfaces. Phys. Rev., Second ser., vol. 100, no. 6, Dec. 15, 1955, pp. 1650-1657.

8. James, Hubert M.; and Lark-Horovitz, Karl: Localized Electronic States in Bombarded Semiconductors. Z. physik. Chem., vol. 198, 1951, pp. 107-126.

9. Blount, E. I.: Energy Levels in Irradiated Germanium. Phys. Rev., Second ser., vol. 113, no. 4, Feb. 15, 1959, pp. 995-998.

10. Blount, E. I.: Energy Levels in Irradiated Germanium. J. Appl. Phys., vol. 30, no. 8, Aug. 1959, pp. 1218-1221.

11. Fan, H. Y.; and Lark-Horovitz, K.: Fast Particle Irradiation of Germanium Semiconductors. Defects in Crystalline Solids, Phys. Soc. (London), July 1954, pp. 232-245.

12. Crawford, J. H., Jr.; and Cleland, J. W.: Nature of Bombardment Damage and Energy Levels in Semiconductors. J. Appl. Phys., vol. 30, no. 8, Aug. 1959, pp. 1204-1213.

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